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THE EFFECT OF VARYING STRAIN-RATIO ON THE HYDRAULIC BULGING BEHAVIOUR OF ALUMINIUM SHEET

by

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The effect of varying strain-ratio on the hydraulic bulging behaviour of aluminium sheet

- by -

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SUMMARY

Annealed commercial-purity aluminium sheet was cold-rolled up to 32%, and the effect of this treatment on the strain-ratio (r) in various directions in the sheet plane was evaluated. Up to approximately 16% cold reduction r_0, r_{45}, and r_{90}, remained approximately constant, while the average strain-ratio, $\bar{r}$, showed no change. At cold reductions in excess of 16% r_0, and r_{90}, fall steadily, while the fall in r_{45}, is less pronounced. Specimens were then 'electromarked' with an array of 0.1 in. dia. circles and bulged, using a pvc 'punch' technique. Plots of natural thickness strain (ϵ) vs. bulge height (h max) show that, for a given height, the strain distribution is more even for an annealed material than for a cold-worked one, due to the effect of work-hardening. The relationship between polar thickness strain and uniaxial uniform elongation (eu) shows a discontinuity at about 10% eu and a further plot of h and $\bar{r}$ against $\bar{e}u$ suggests that this is associated with the change in strain-ratio. Thus, bulge height increases linearly with increasing uniform elongation at a constant strain-ratio, but in a more complex fashion with varying strain-ratio. Increased $\bar{r}$ gives decreased ϵ at the pole, producing a more even strain distribution over the bulge.

Contents

Introduction

Sheet-metal pressing, the plastic deformation of sheet metal by the use of a punch, die and blankholder, is conventionally subdivided into interacting parts such as radial drawing, plastic bending under tension and stretch forming. Other factors to be considered are, free bending, friction, and tendency to fail due to compressive instability, i.e. buckling. The prediction of the performance of a sheet metal under a double-action press can be extremely difficult, for it is often not possible to say which of these conditions obtain and which is dominant. For this reason, simulative tests such as the Erichsen[1] or Swift tests,[2] while perhaps ranking different materials satisfactorily for one operation, will give the wrong ranking in another. This sort of result, coupled with the non-simulative scale and frictional effects[3,4] make these tests very limited on their application to material performance. The alternative approach[5] is to measure properties in a tensile test - yield-strength strain-ratio, tensile-strength, elongation, work-hardening exponent, for example - and rank material on the basis of past experience of the effect of these properties on metal behaviour in the particular situation being studied. The disadvantages of both these systems can be understood. Nevertheless, if the dissection of sheet metal pressings into simple deformation modes is accepted, then it would seem logical to try to associate certain material properties with these modes, if this were possible. Taking the simplest case of a sheet-metal forming operation containing radial-drawing, plastic bending-and-unbending under tension, and stretching, (Fig. 1) it can be seen that - and experiment confirms this - to a first approximation the two important strain situations are plane strain from $A \rightarrow B$, and strain due to an imposed biaxial tension from $B \rightarrow C$. Plane strain is postulated from $A \rightarrow B$ assuming $d\epsilon_z = 0$ in the flange - due to constant spacing between the blank and the die, and $d\epsilon_y = 0$ in the cup wall, due to the restraining influence of the punch. (Fig. 2). Over the punch nose, the strain is $\neq 0$ in the x, y or z directions, and results from biaxial tension imposed by the action of the punch against the restraining effects of blankholder and die-friction on the blank.

The most important material properties which influence the sheet-metal forming operation are at present thought to be the strain ratio, $\underline{r}$, and the limit of uniform elongation in the tensile test, whether this is measured directly or indirectly and quoted as strain or as an $\underline{n}$ value, (hereinafter called eu.). The plane strain conditions in the cup wall and over the radii preclude circumferential straining, and so thinning must occur to maintain volume constancy. Stresses are tensile, σ_y being the proportion of σ_x required to give $d\epsilon_y = 0$. From this picture it can be seen that any property variation which can alter σ_z without altering σ_y will affect the resistance of the blank to plastic thinning. The index of this property is the strain ratio, $\underline{r}$, the ratio of width strain to thickness strain, measured at a stated elongation and at a stated orientation to the rolling or other fixed direction, in a tensile test. $r = 1$ for an isotropic material and greater than unity for an anisotropic metal which resists thinning. r is closely associated with crystallographic texture, and can vary in the plane of the sheet. It is important to distinguish between planar and normal anisotropy, the former giving rise to earing, while the latter, other factors being equal, controls drawability (Fig. 3). The effect of eu on drawing is shown in Figure 4, which indicates that for a material with a stress-strain curve which can be represented by $\sigma = K\epsilon^n$, that the depth of draw, when failure occurs conventionally over the punch profile radius, is virtually unaffected by wide variations in this property.[6] However, the straining over the punch nose is markedly influenced by elongation[7] (Fig. 5) some correlation would be expected between instability strains under different stress systems.

Thus a state of affairs exists where two strain situations (approximately) describe the sheet-metal forming operation and two material parameters are agreed to be of prime importance.

So far there has been no study of the effect of r on biaxial stretching; it is the purpose of the present work partially to repair this omission.

Materials

The material used in the present investigation was hard-rolled commercial purity aluminium coil $5\frac{1}{2}''$ x $0.036''$ of nominal chemical composition as follows:

Al	Cu	Mg	Si	Fe	Mn	Ni	Zn	Pb	Sn	Ti	
99.0 min	0.1	0.1	0.5	0.7	0.1	0.1	0.1	0.05	0.05	0.1	wt.%
				. . .	max	. . .					

Heat Treatment

All samples for the present investigation were heat-treated in an air-circulation furnace at 360°C for thirty minutes. The sheet samples were evenly spaced in a rack and this was not placed in the furnace until the desired temperature was reached.

Cold Rolling

Cold rolling of the annealed aluminium was carried out on a Stanat-Mann two-high mill. The roll dimensions were $5\frac{1}{2}''$ diameter by $8''$ width, and the rolling speed used was 24 ft/min and was kept constant for the different reductions. The rolling mill was capable of reduction to an accuracy of $0.0001''$.

Hydraulic Bulging

Bulging was carried out on a 35-tons-maximum-load Hille-Engineering press fitted with an X-Y recorder for measurement of load and height. The press was capable of applying a maximum blankholder load of 8 tons, and the maximum was used to prevent drawing-in of the blank during the bulging operation. A flexible thiokol-rubber punch was used to simulate hydraulic pressure as described by Pearce[8]

Tensile Testing

Polycrystalline tensile-test specimens were manufactured according to BSS 18. An Instron tensile-testing machine was used and a load-elongation curve was autographically recorded. This machine is a hard-beam type which incorporates an electronic weighing system for detecting the tensile load. The chart for recording load and strain is driven synchronously with respect to the crosshead which strains the sample held in two grips. All tests were carried out at a strain rate of 0.1″ per minute.

Measurement of thickness in bulged specimens

The thickness over the profile of hydraulically-bulged specimens was measured by a dial-gauge clamped securely by an permanent magnet to a metal stand containing a spherical steel ball 0.75″ diameter. Figure 6 shows a bulged specimen in position for measurement of thickness at one particular element.

Grid-marking

The positions for thickness measurement were obtained by marking a grid on the material before bulging. The grid consisted of 0.10″ diameter circles in 0.25″ squares, etched onto the material by an electrolytic process ('Electromark'). A low-voltage current was passed between a power-unit and the work-piece by means of an electrolyte. The circles and squares on a stencil were the only areas of contact between the power-unit and work-piece and when the current was passed these were etched onto the surface.

Experimental

Preliminary tensile tests were carried out on material after annealing as described previously (page 2) and on annealed material cold-rolled 8%, 16% and 32%. The results of these tests indicated that very little change in r-value occurred up to 16% cold reduction, and with the range of elongations obtained, a programme for the experimental work was established.

The following range of reductions were carried out, to obtain the conditions of varying ductility required, which are shown against their respective identification code letter:-

Cold Reductions	0% (as annealed)	2%	4%	6%	8%	12%	16%	20%	24%	32%
Code letter	A	B	C	D	E	F	G	H	I	J

The aluminium sheet was cut into lengths of the required size to obtain three tensile-specimens and two-bulge-test specimens. These specimens were annealed and cold-rolled to one of each of the above reductions. This procedure was also used for a repeat series of specimens. Tensile-test specimens of 2″ parallel gauge-length were cut in direction 0°, 45° and 90° to the rolling direction, to measure any planar anisotropy that existed. The specimens were milled to the required width from over-size strips cut from the sheet. The width of each specimen was within ± 0.001″ of the nominal 0.500″.

2-cm. length and 1 cm. width gauge lengths were scribed in the central portion of the specimens. In the case of the 32% cold-rolled specimens three gauge lengths were used. Tensile-tests were carried out on the prepared specimens, where the strain ratio r and uniform elongation (e_u) were measured during the test. The total elongation (e_t) was measured directly from the specimen after fracture and the ultimate tensile strength was calculated from the maximum load reached during the test, which was obtained from the autographically plotted load-extension curve.

Measurement of strain ratio and elongation

The strain-ratio measurements were taken at three different strains during the test, on removal of the load, at approximately equal intervals of strain below the point of instability.

The strain ratio r was then calculated by the formula:

$$r = \frac{\log_e \frac{w_o}{w_f}}{\log_e \frac{w_f l_f}{w_o l_o}}$$

where:
w_o = original width
w_f = final width
l_o = original length
l_f = final length.

The uniform elongation (e_u) is a measure of the engineering strain at instability and thus requires the measurement of original length and final length at this point. As instability is the position of maximum load, i.e. dp = 0 which is a flat portion of the load-extension curve, it is often difficult to observe its position precisely and thus measure the uniform elongation accurately. In the present work to standardise the measurement of e_u the final length measurement was taken at a 0.5% load drop after instability. A vernier microscope was used to measure the original and final lengths in the case of e_u and for the length and width measurements for calculating the r-value. The total elongation (e_t) was measured after fracture on a 2″ gauge length previously scribed on the specimens.

Hydraulic bulging

As the material had been cold-rolled by different degrees to obtain the different ductilities, it was necessary to investigate the effect of thickness on the hydraulic bulging operation. Samples of the annealed material which were at the initial thickness of 0.036″ were electro-polished to several different thicknesses to cover the range of cold reductions. Electropolishing was carried out using acetic-perchloric acid electrolyte at a current of 6-amps with a potential of 20 volts. The specimens, with one side lacquered, were placed at the anode and an aluminium cathode was used.

Blanks 4″ diameter were cut from the electropolishing material and bulged; the height at fracture being measured with a dial-gauge fitted to the press.

Blanks of a similar size were also cut from the specimens in the different temper conditions, two from each condition, four from B and D conditions; these were bulged and height measurement on a dial-gauge were noted for increments of load on the X-Y recorder. It was not possible to use the X-Y recorder for height measurement due to the compression of the rubber punch.

Two further blanks from each of the different conditions were bulged and at increments of 0.1″, removed and the thickness measured in positions originally 0.10″ apart. Twenty thickness readings were taken in the above positions radially from flange to flange. Scans were also taken at 0° and 90° to the original rolling direction.

Results and discussion

Accuracy

Strain ratio

The strains were measured using a travelling microscope reading to ± 0.001 cm. and the estimated accuracy of r was ±1% for the higher ductility materials. (A, B, C, D and E). Greater error existed in the measurements on specimens F to J possibly rising to 10% for J, where the gap between yield and instability is short and ill-defined.

Uniform elongation

These were made similarly to the r value measurements, any errors arising from the estimation of 0.5% drop in load, but these were considered to be small.

The total elongations had an estimated maximum error of 10%.

Height measurements

The dial-gauge used could be read to ± 0.001″ and the error was less than 1%. Through-thickness measurements were made with a dial-gauge reading to ±0.0001″ and the error was less than 1%.

Results

Uniaxial Tests

The uniaxial results are shown in Figures 7, 8, 9 and 10. The points shown are the averages of three tests in each condition and direction and the average r, etc., i.e. $\bar{r}$, $\bar{e}_u$, $\bar{e}_t$, and $\overline{TS}$ are calculated from weighted equations of the type:

$$a = \frac{(l + 2d + t)}{4}$$

a = property

l = value in longitudinal direction

d = value in diagonal direction

t = value in transverse direction.

From these figures it can be concluded:

(1) r, r_o, r_{45}, and r_{90} show gentle changes with increasing percentage cold reduction until 16% cold reduction is reached.

(2) $\bar{e}_u$, e_{u_o}, $e_{u_{45}}$ and $e_{u_{90}}$ show a fall with increasing cold reduction with a sharp change in slope of the curve at 16%.

Biaxial Tests

The metal thickness (0.036 in.) has obviously been reduced by the cold rolling and for the 16% cold-reduction sample it is now 0.030 in. Before commencing any bulging tests the effects of gauge variation on bulge height must be examined. Hill[9] when discussing the deformation of a circular metal diaphragm obtained a relationship between stress and strain at instability by assuming that the particles in the diaphragm describe circular paths orthogonal to the momentary profile. On this assumption:

$$\epsilon_3 = -2 \ln\left(1 + \frac{h^2}{\underline{a}^2}\right)$$

where ϵ_3 = through-thickness of strain at the pole

h = polar height

$\underline{a}$ = initial blank radius,

and, as $\underline{a}$ is a constant in this investigation, this suggest that h is uniquely dependent on ϵ_3, that is, gauge has no effect.

This is confirmed in Figure 11, where a constant bulge height of about 0.93 in. is obtained with a gauge variation of 0.029 - 0.036 in. The relationship between height at fracture and $\bar{e}_u$ and $\bar{r}$ for all materials prepared is shown in Fig. 12. The heights shown are corrected for the difference in thickness which has occurred at the pole during the bulging operation. This was necessary because the height measurement was taken on top of the blank and is thus lower than the true height, by the amount of thinning which has occurred. Only a small scatter-band existed for the four tests in each condition and the maximum scatter was observed in the 32% cold rolled material which was $\mp$ 4% of the average height. Fracture of all the specimens occurred close to the pole and either in the longitudinal or transverse directions; never in the diagonal direction.

Also it was noted that in the least work-hardened state the material exhibited instability before fracture, but this was not so for the highly work-hardened condition. This effect was similar to that observed by Mellor[10]. The thickness measurements taken radially over the blanks were converted to natural thickness strain, i.e. $\ln(t_o/t)$ where t_o and t are the original and final thicknesses respectively. The thickness strain was plotted against initial radial distance for the series of heights measured.

Discussion

A plot of average bulge height at fracture versus the average uniform elongation of the particular specimen tested is shown in Fig. 12 (lower). This illustrates that the rate of increase of height decreases in the initial region of increasing uniform elongation up to 10%. Above 10% $\bar{e}_u$ the relationship is seen to be approximately linear. However, if the r-value is also plotted against bulge height (Fig. 12 upper) then it can be seen that the change from the linear behaviour occurs at the significant change in r-value. To show the effect of r-value on the bulging operation values of strain at the pole at heights of 0.4 , and 0.5 and 0.6 were plotted against $\bar{e}_u$ (Fig. 13), the results taken from Figures 14 - 21. The uniform elongation was used as a parameter for the above correlation because different strains at the pole would be expected for the specimens of varying ductilities bulged to the same height. Figures 14 - 21 show a trend of increasing strain at the pole with decreasing uniform elongation as would be expected. However, at about 10% elongation a change in the slope occurs with a greater increase in strain at pole for decrease in elongation.

This change in polar through-thickness strain occurs at a similar elongation to the change in the height at fracture against elongation curve. Both the above changes occur at positions where a significant change in the r-value has occurred. Thus the r-values seems to have an important effect on the strain at the pole and failure. As the specimens in Figures 14 - 21 were considered for the same heights reached on bulging, and different strains at the pole were observed, it indicates that the strain distribution varies with the varying ductility and a greater change in strain distribution is found for materials of lower r-values.

Conclusions

The results obtained show an effect which a change in the normal anisotropy parameter produces in biaxial deformation. Decreasing $\bar{r}$ gives higher strains at the pole, while the reverse produces a more even strain distribution, i.e. a less steep strain gradient between the pole and the flange. If normal anistropy is regarded as a measure of the through-thickness work-hardening behaviour then the following model may be proposed.

For $\bar{r} = \infty$ the through-thickness flow-stress will be infinity and so, as balanced biaxial tension can be equated to through-thickness compression, apparently, no deformation can take place and failure will occur at a very low bulge-height with low fracture-strain. A metal of very high $\bar{r}$ value, one with very few z-direction slip-systems operating, should fail with a brittle fracture almost as soon as deformation commences.

A material with $\bar{r} = 0$, on the other hand could also give low bulge-heights, and early failure could occur due to the very low flow stress in the through-thickness direction. In a metal, slip would occur exclusively on the favourable slip-systems in the z-direction and so the strain developed would virtually be the commencement of the neck which preceded fracture. Thus a low bulge-height would again result, but in this instance with a high fracture strain.

So, the correct value of e_u and r for the particular metal being bulged is required, firstly, to give the most even strain distribution possible, and secondly, to give the maximum value of fracture strain. In this way, the deepest possible cup produced under biaxial tension will result.

Acknowledgements

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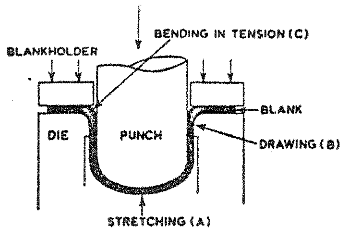

FIG. 1 A SIMPLE SHEET-METAL FORMING OPERATION

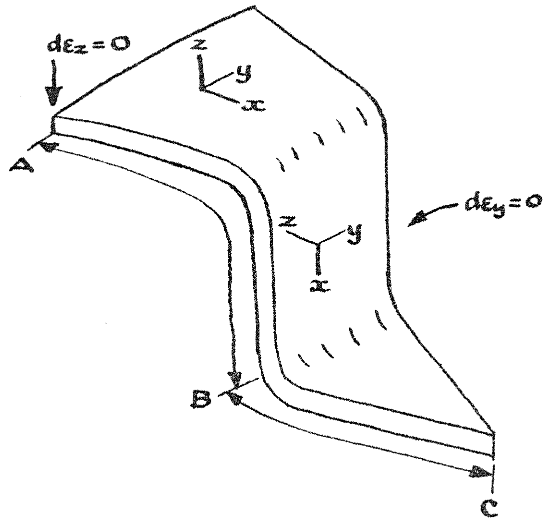

FIG. 2 THE STRAIN CONDITIONS IN THE FLANGE, WALL AND BASE OF A SIMPLE CUP

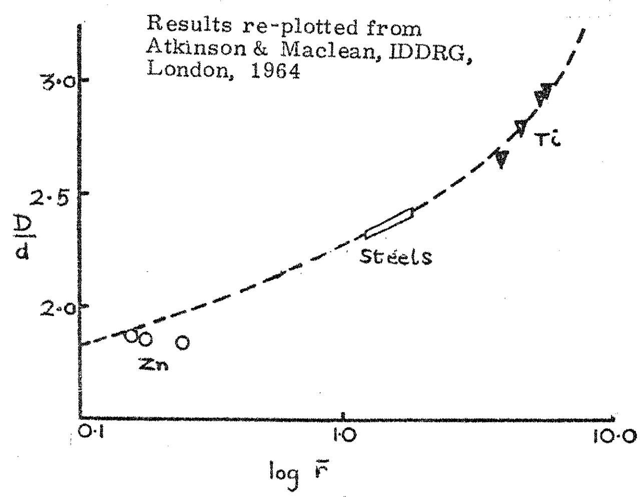

FIG. 3 RELATIONSHIP BETWEEN THE STRAIN RATIO ($\bar{r}$) AND THE LIMITING DRAWING RATIO

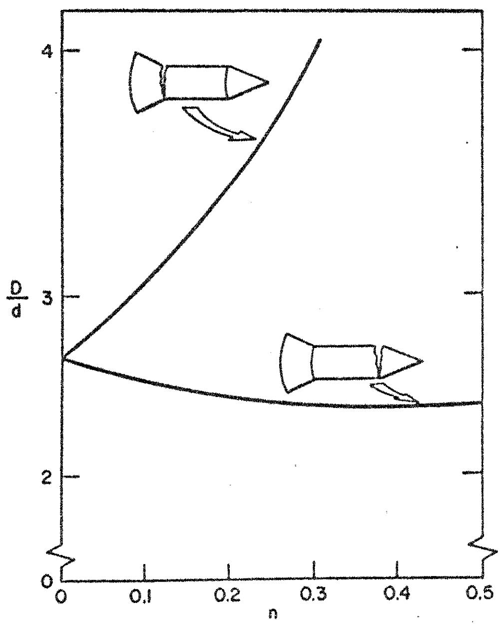

FIG. 4 RELATIONSHIP BETWEEN THE WORK HARDENING EXPONENT (n) AND THE LIMITING DRAWING RATIO

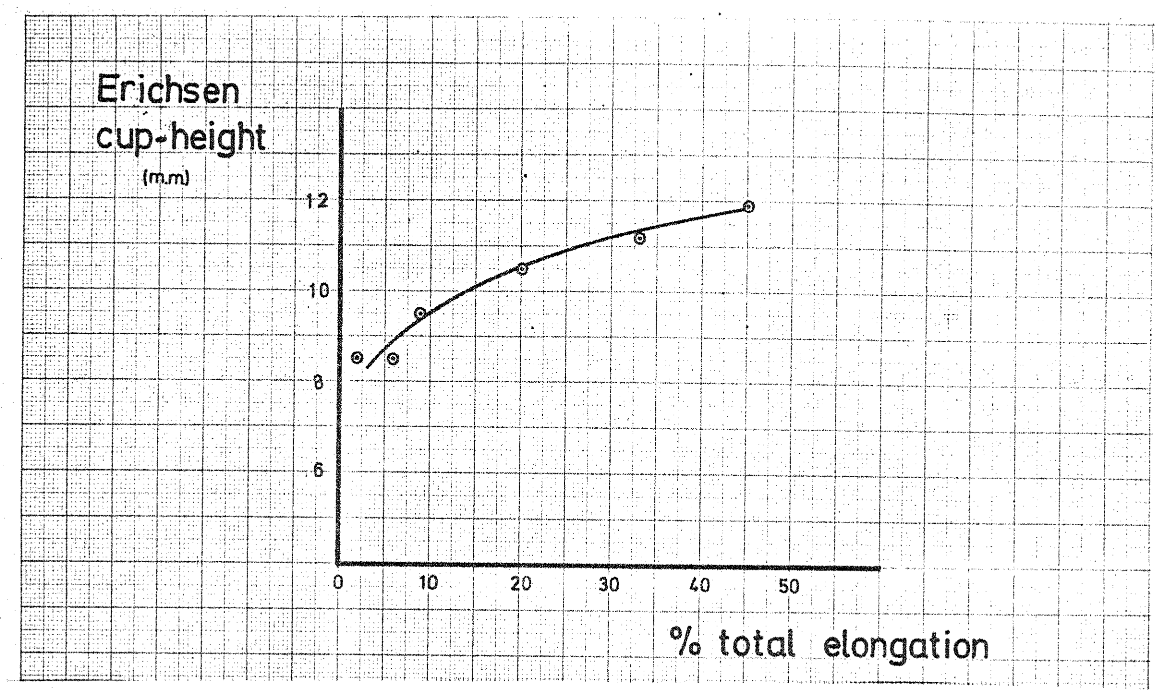

FIG. 5 A RELATIONSHIP BETWEEN DUCTILITY AND ERICHSEN VALUE

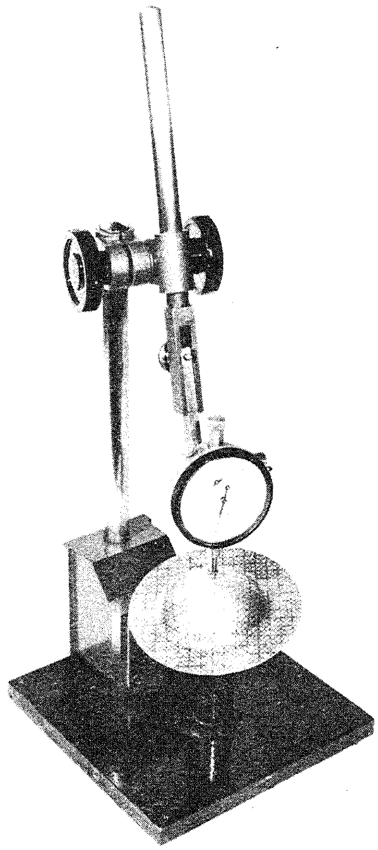

FIG. 6 RIG FOR THICKNESS MEASUREMENTS

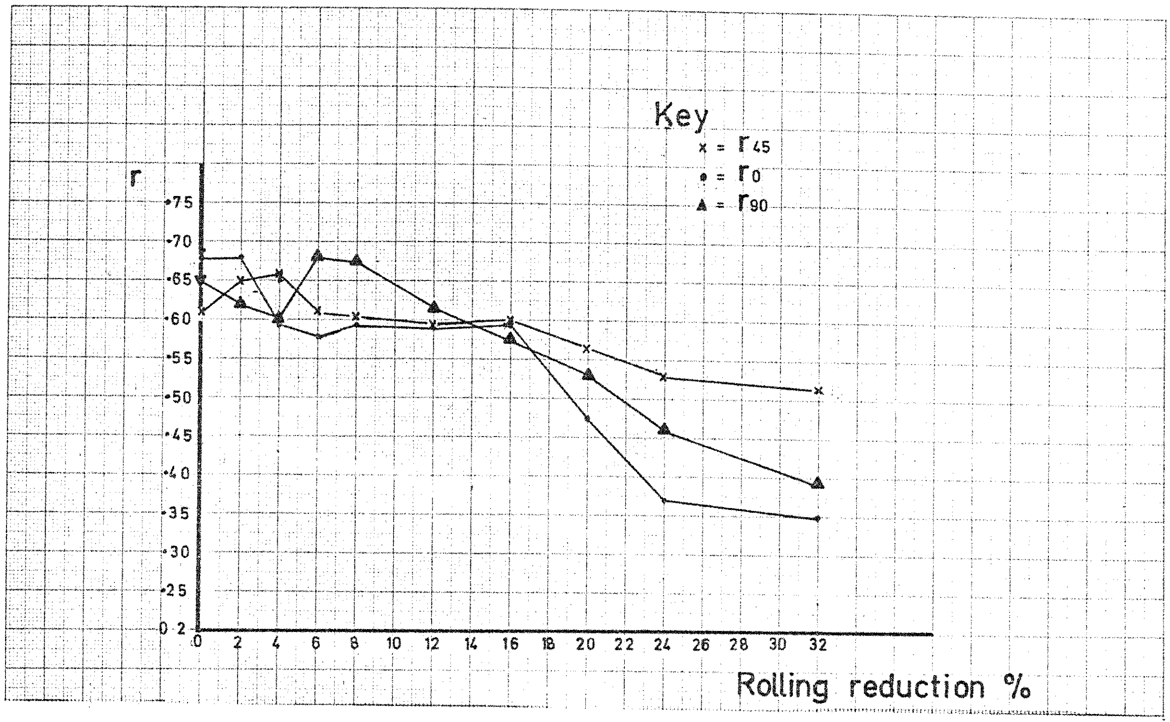

FIG. 7 RELATIONSHIP BETWEEN PERCENTAGE COLD REDUCTION AND STRAIN RATIO MEASURED AT SPECIFIED ANGLES TO THE ROLLING DIRECTION

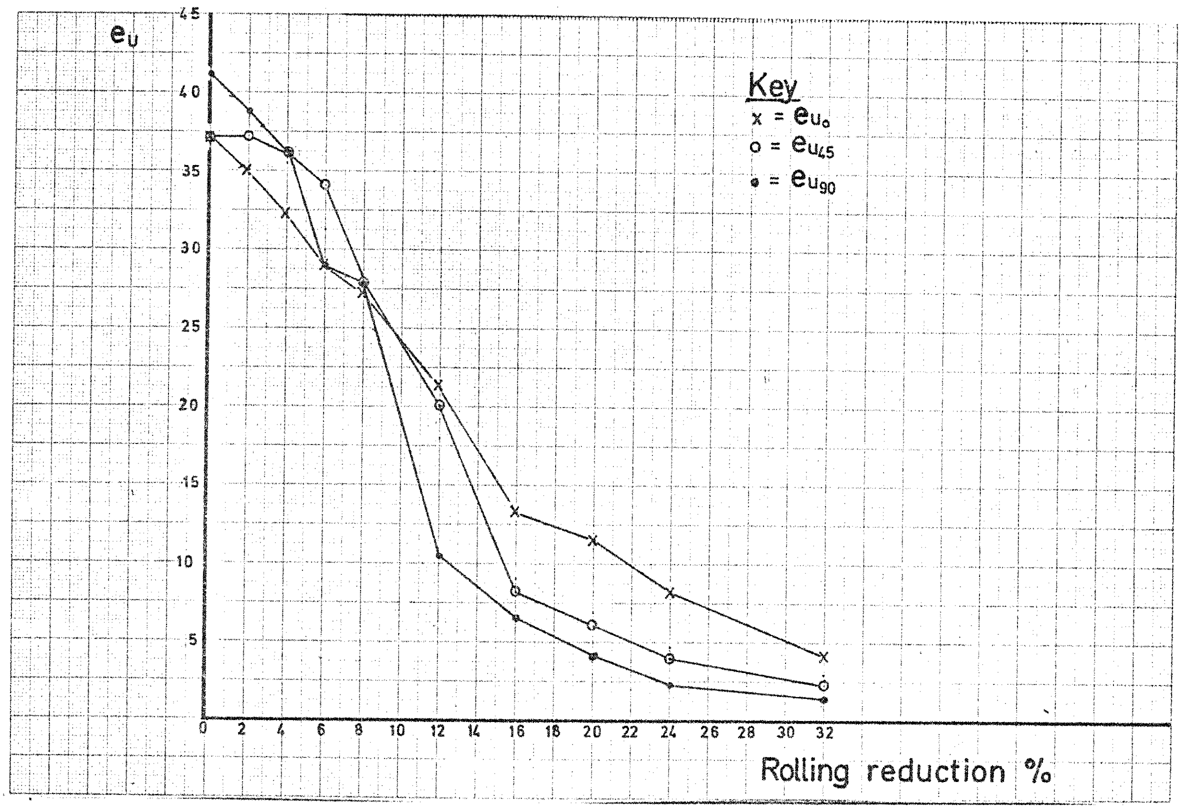

FIG. 8 RELATIONSHIP BETWEEN UNIFORM ELONGATION MEASURED IN STATED DIRECTIONS TO THE ROLLING DIRECTION AND PERCENTAGE COLD REDUCTION

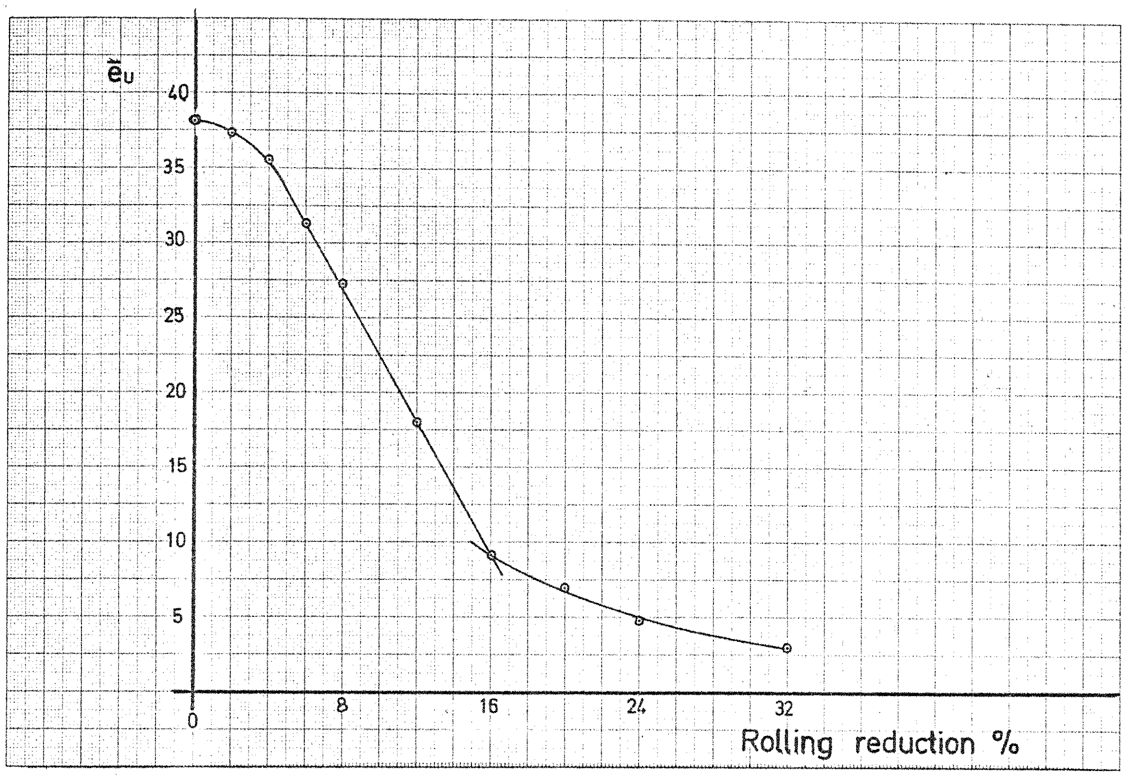

FIG. 9 RELATIONSHIP BETWEEN AVERAGE UNIFORM ELONGATION AND PERCENTAGE COLD REDUCTION

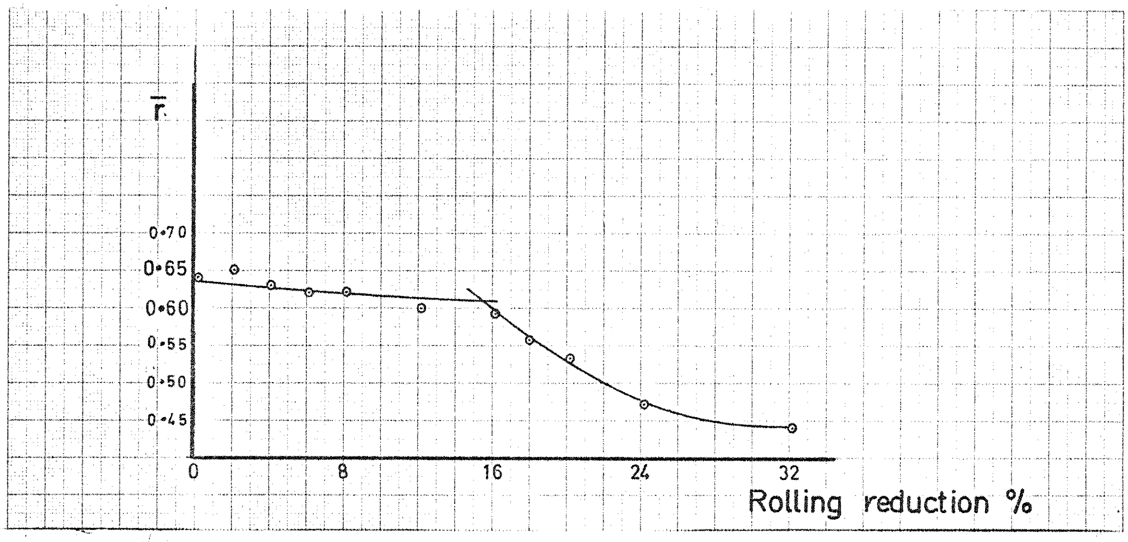

FIG. 10 RELATIONSHIP BETWEEN AVERAGE STRAIN RATIO AND PERCENTAGE COLD REDUCTION

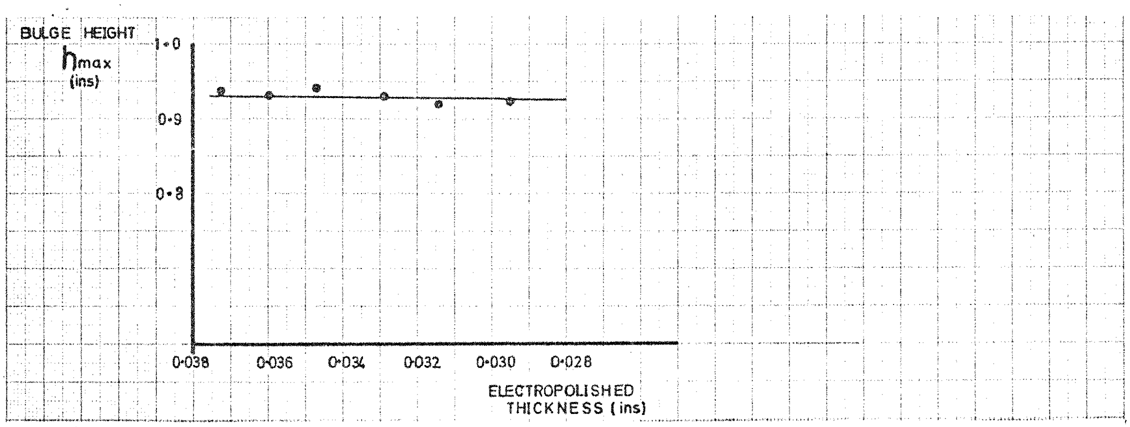

FIG. 11 RELATIONSHIP BETWEEN BULGE HEIGHT AND SHEET THICKNESS

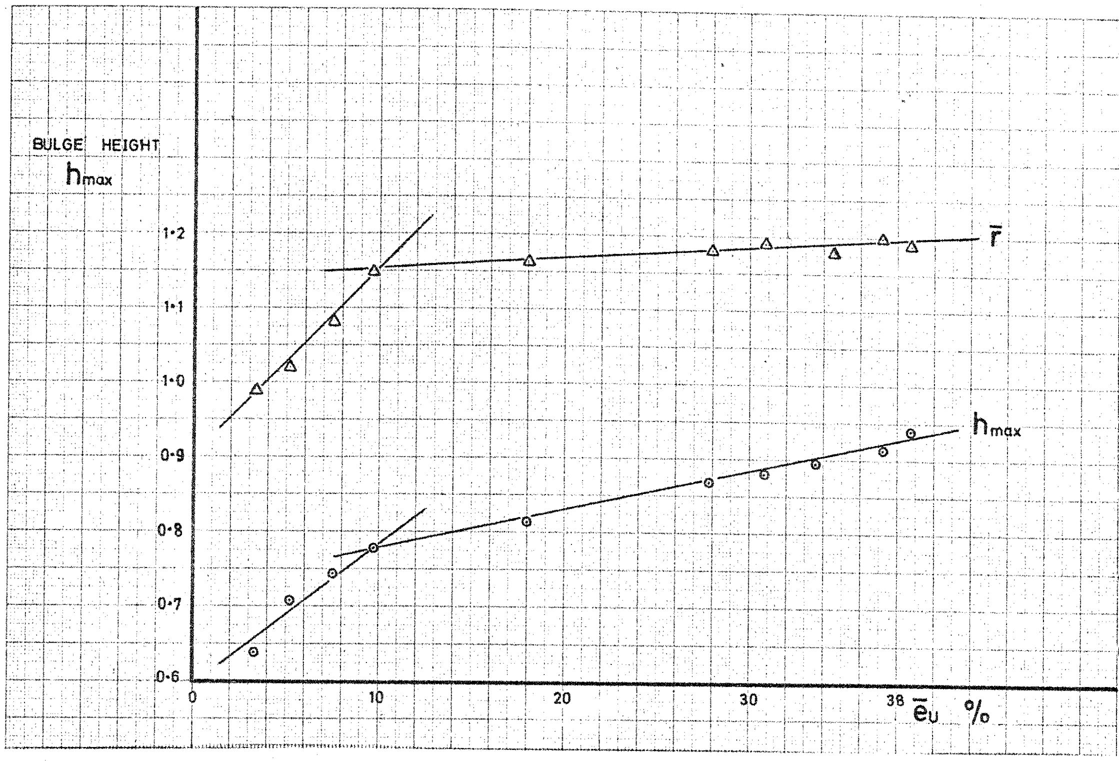

FIG. 12 RELATIONSHIP BETWEEN AVERAGE STRAIN RATIO AND BULGE HEIGHT AND AVERAGE UNIFORM ELONGATION

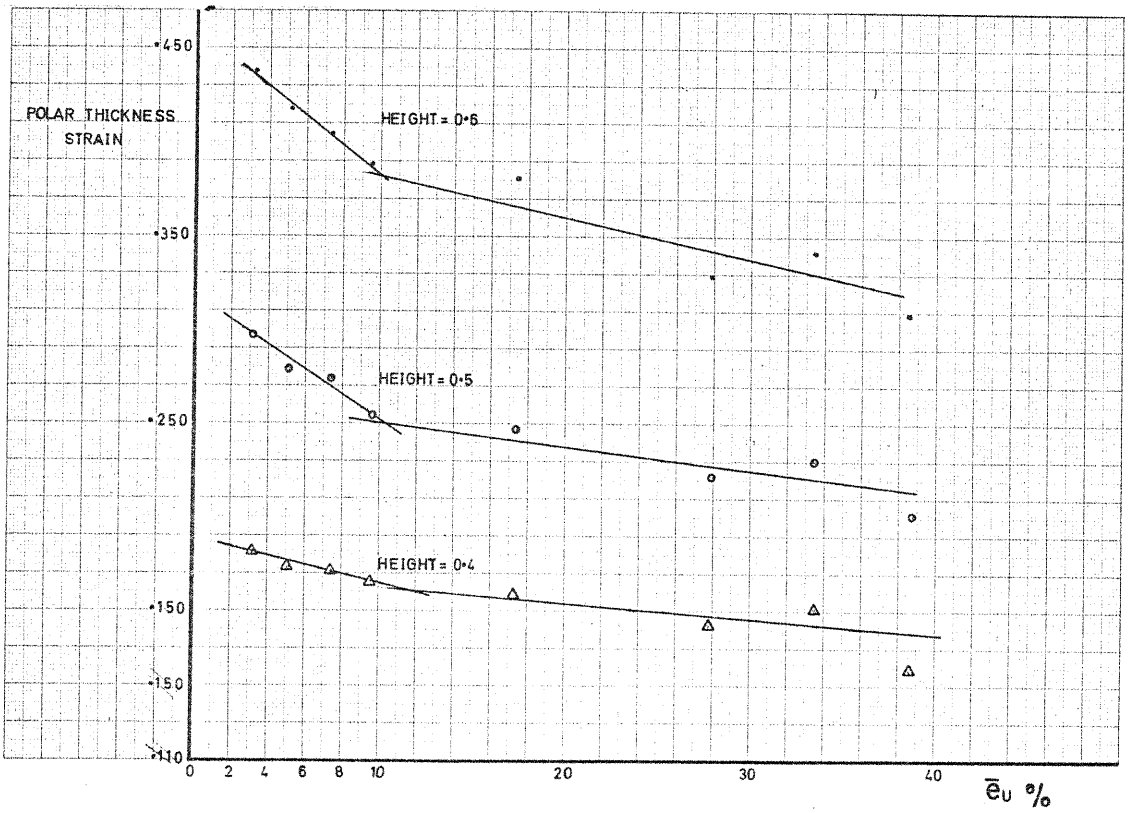

FIG. 13 RELATIONSHIP BETWEEN THICKNESS STRAIN AT THE POLE AND AVERAGE UNIFORM ELONGATION

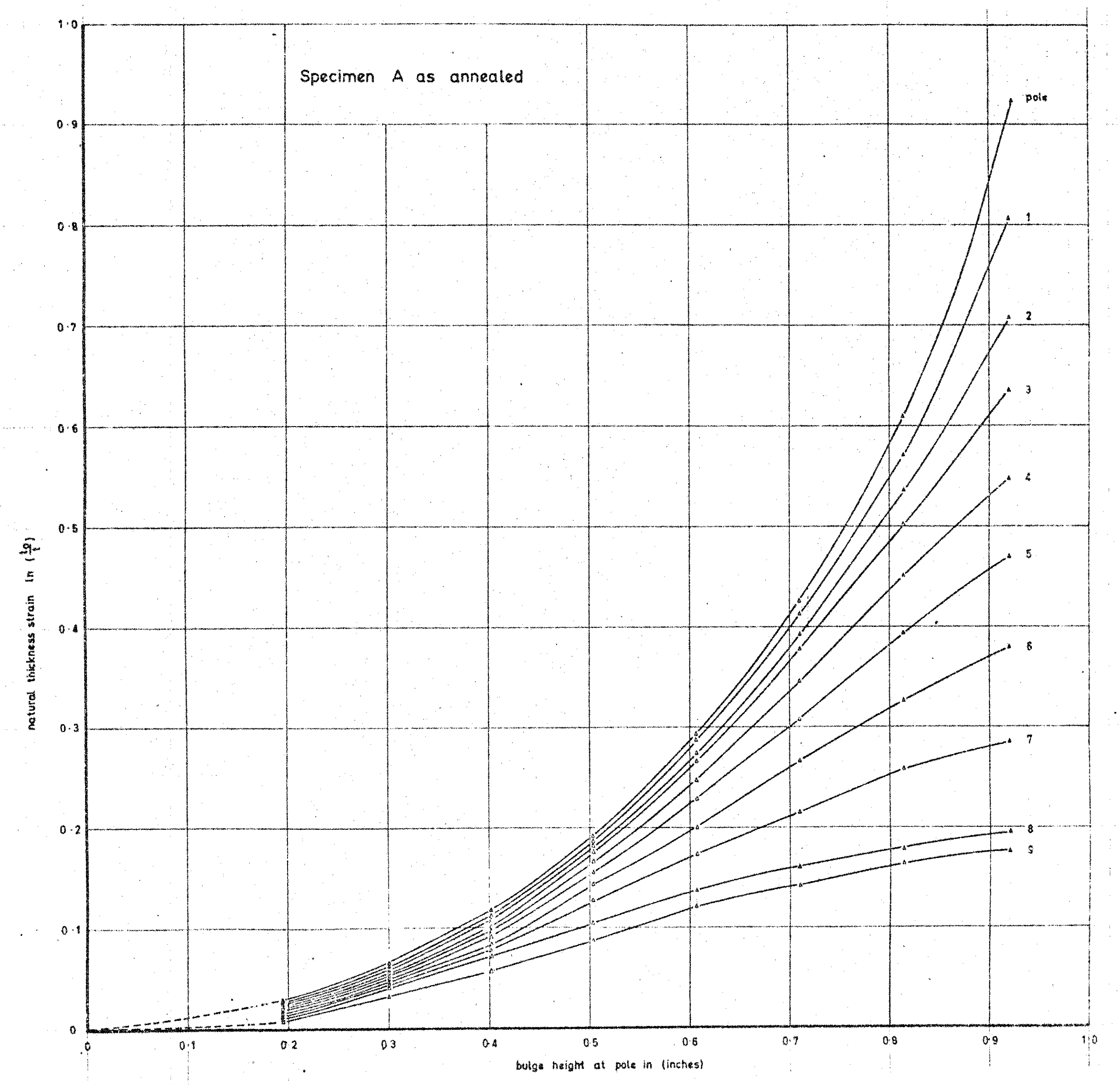

FIG. 14 RELATIONSHIP BETWEEN POLAR BULGE HEIGHT AND THICKNESS STRAIN

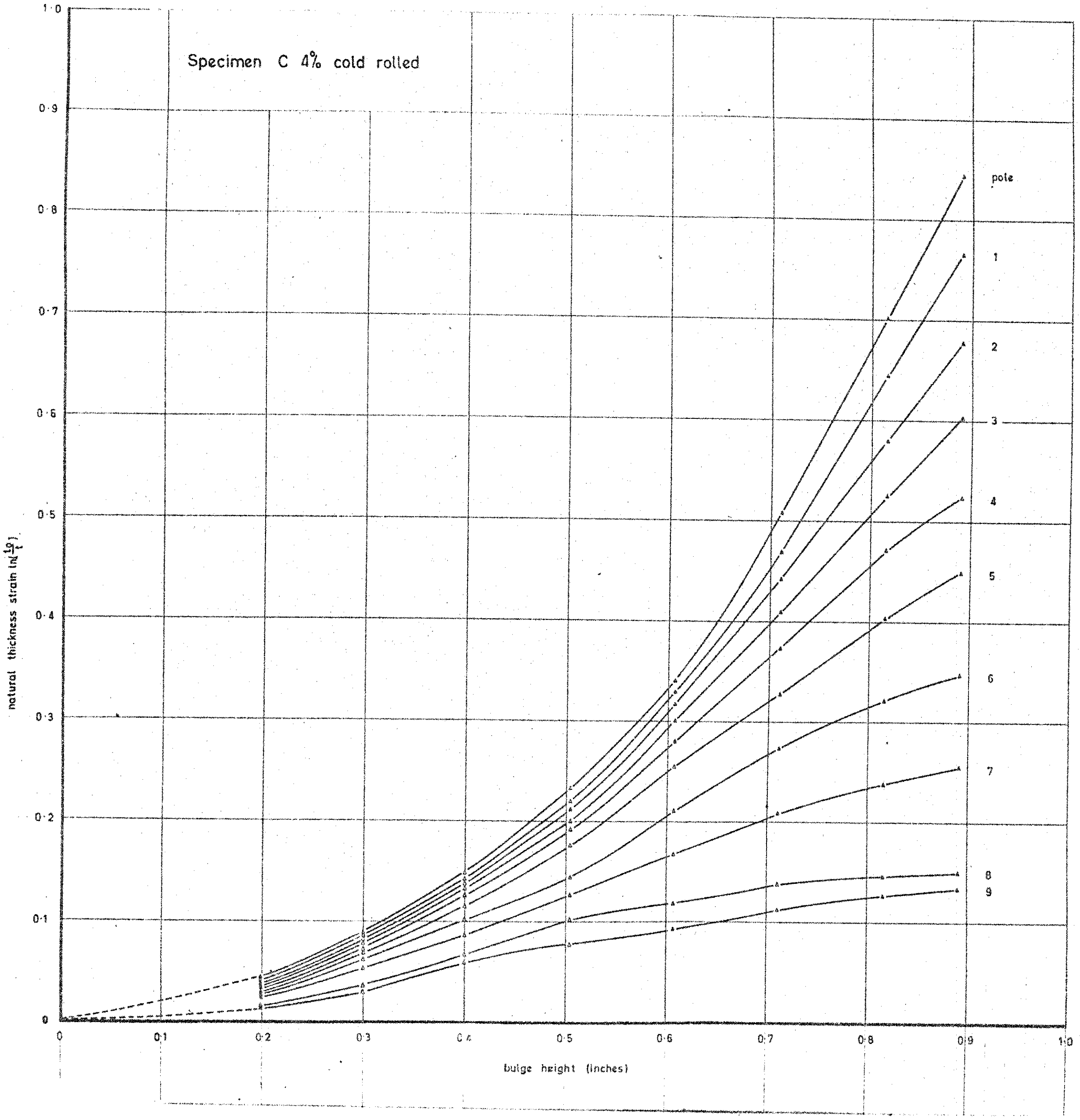

FIG. 15 (as figure 14)

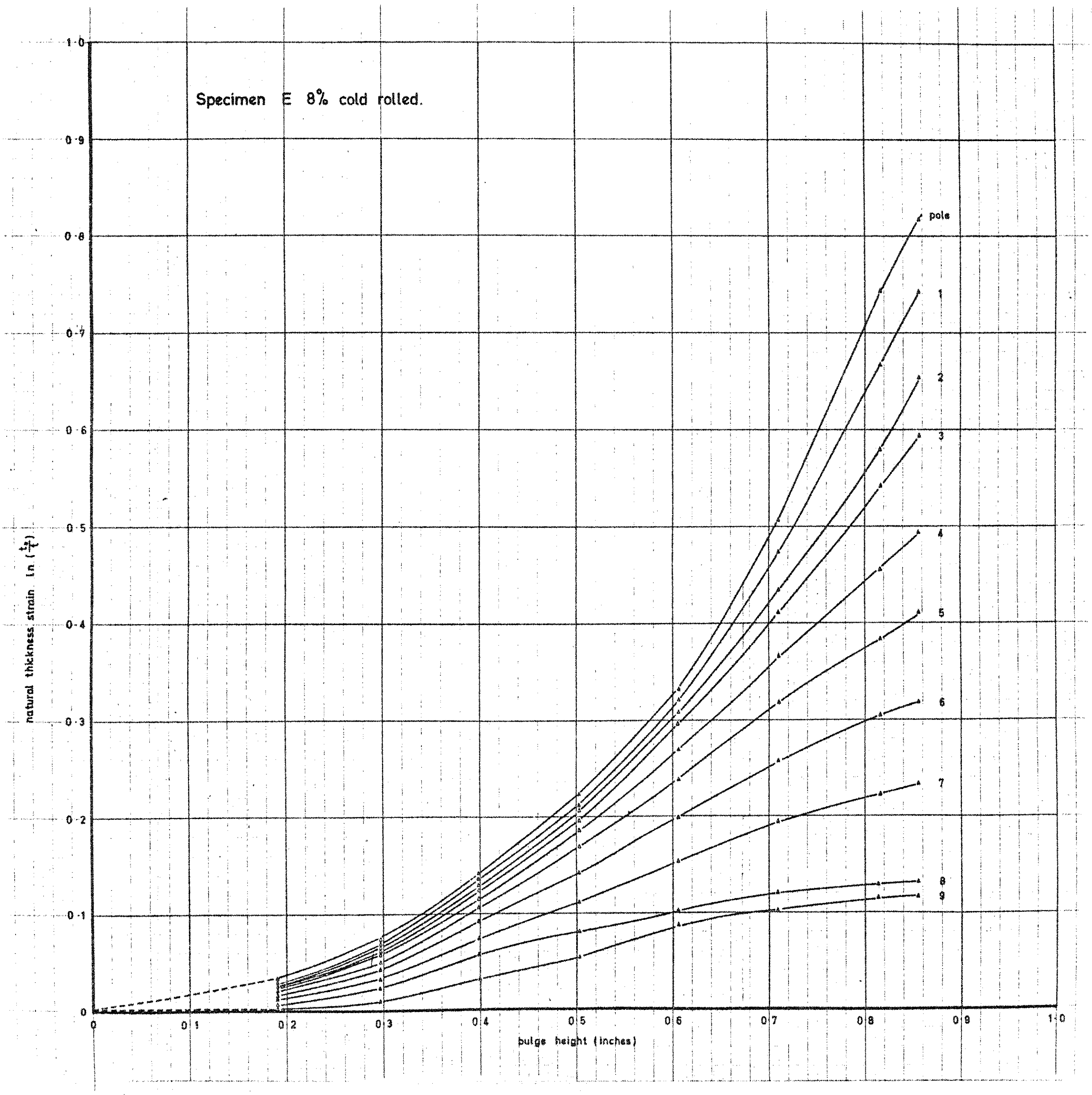

FIG. 16 (as figure 14)

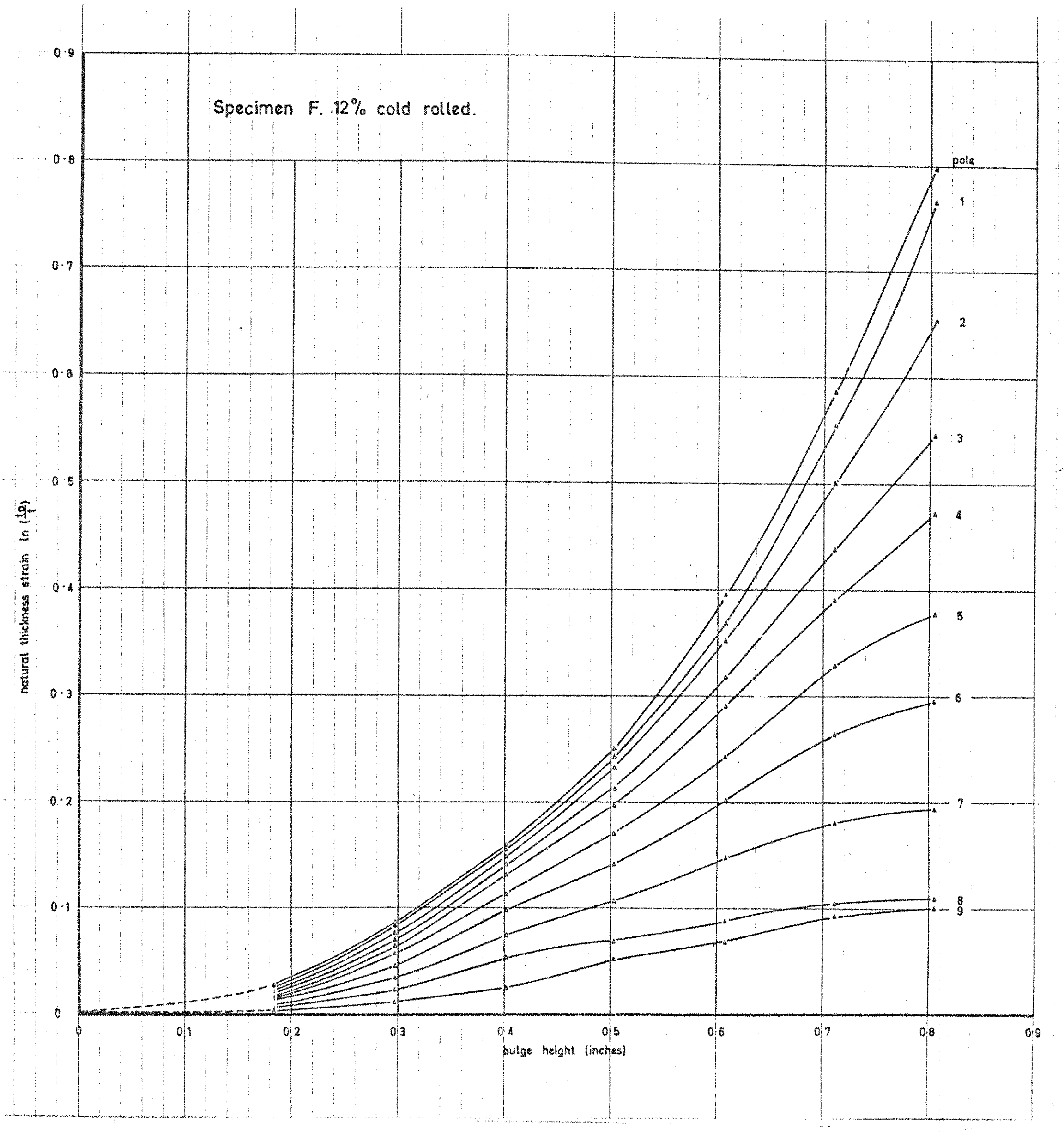

FIG. 17 (as figure 14)

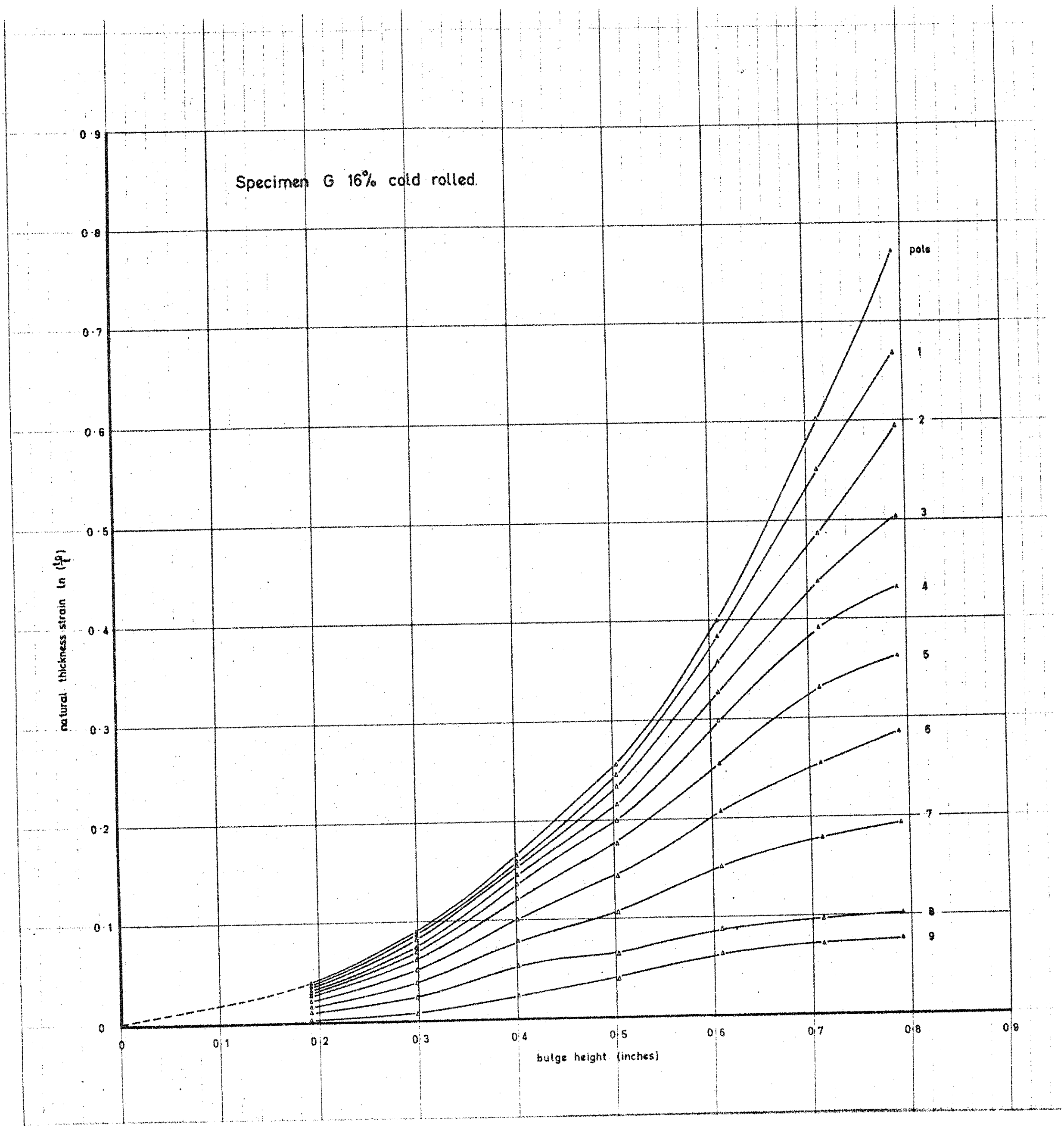

FIG. 18 (as figure 14)

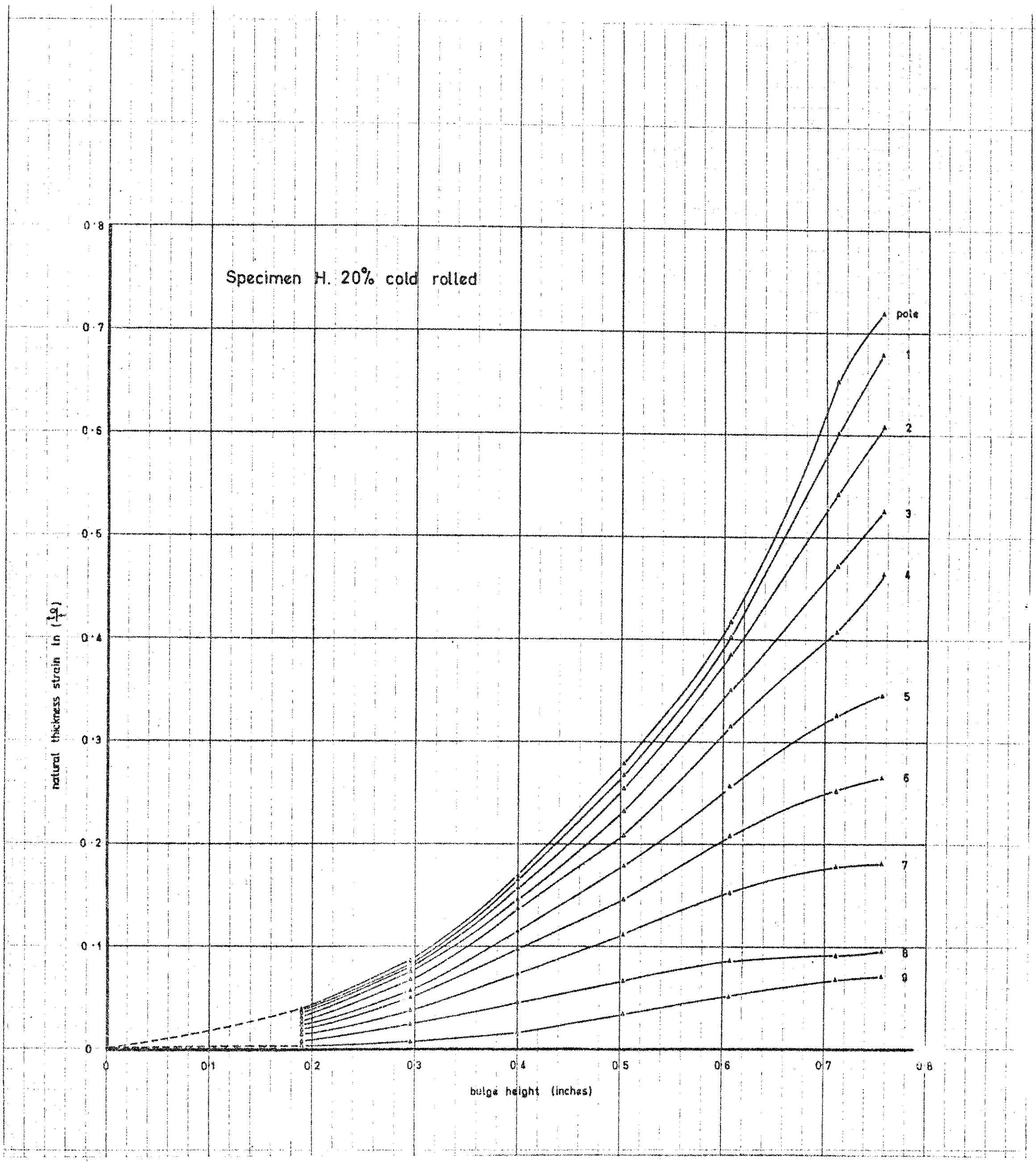

FIG. 19 (as figure 14)

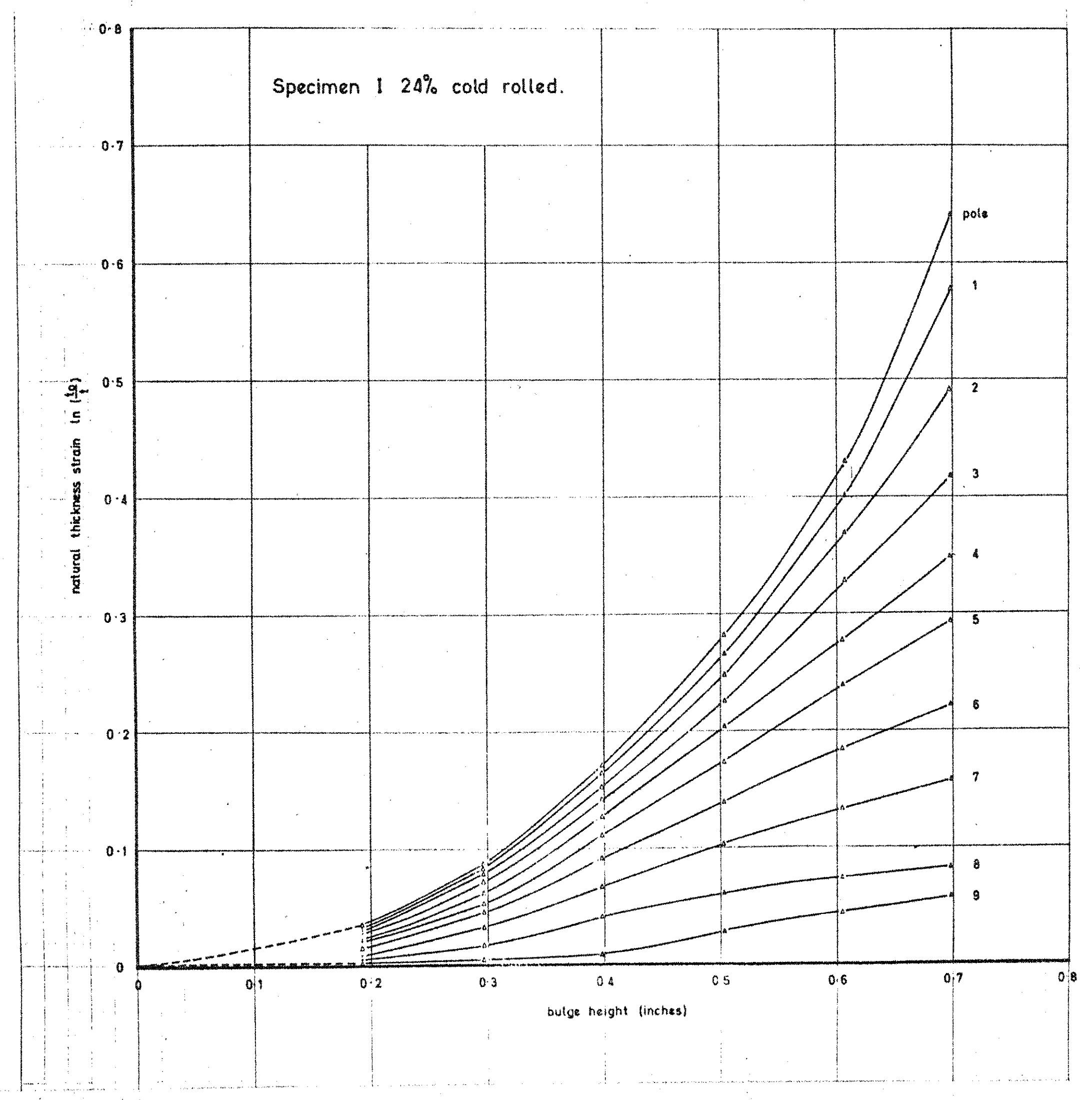

FIG. 20 (as figure 14)

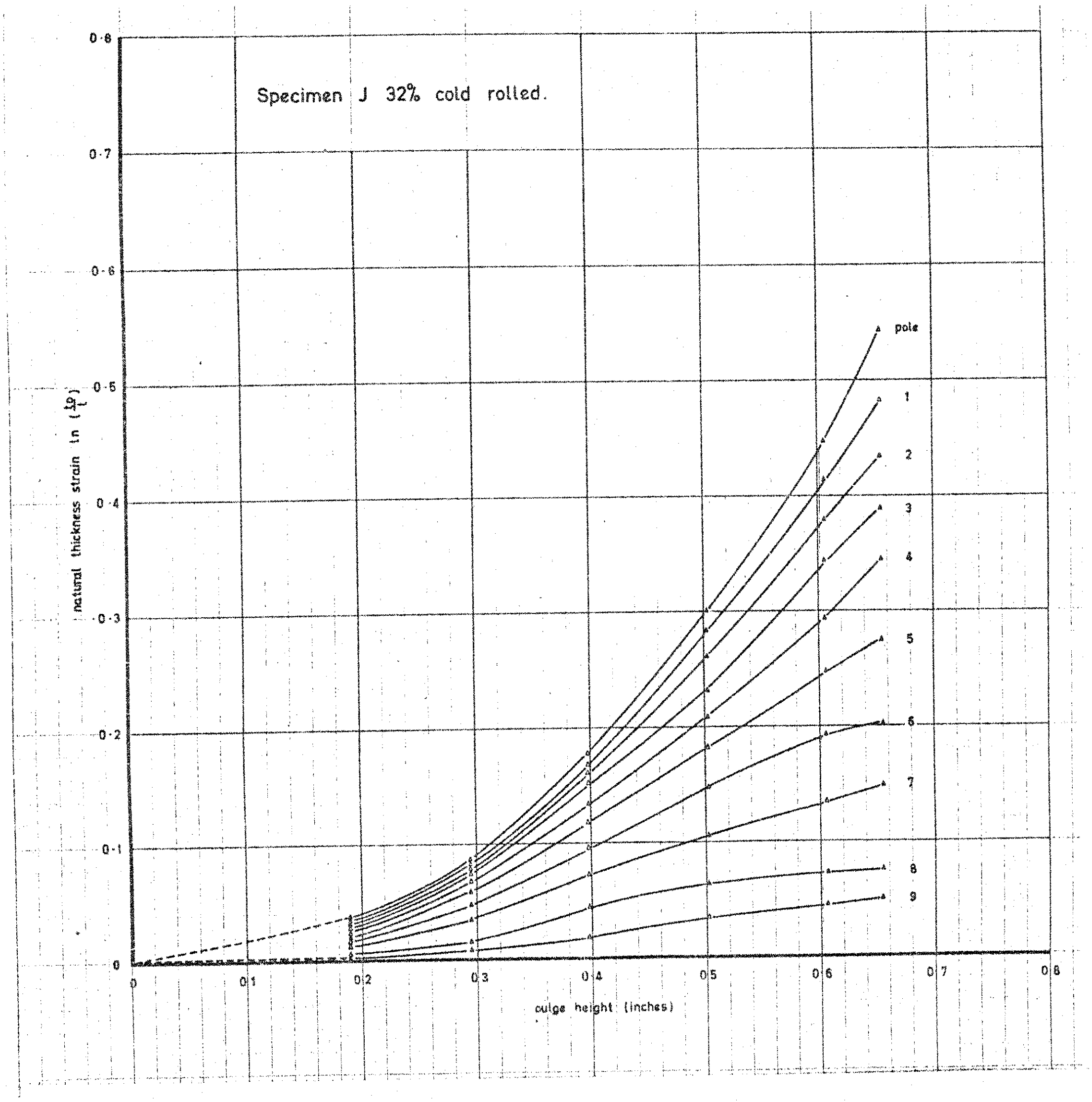

FIG. 21 (as figure 14)